Perceptual Attributes in Product Design: Fuel Economy and Silhouette-Based Perceived Environmental Friendliness Tradeoffs in Automotive Vehicle Design

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The quest for improved fuel efficiency and environmental friendliness is transforming automotive vehicle design. In addition to new energy sources and management, new powertrain technologies offer increased flexibility in the spatial arrangement (packaging) and exterior shape (styling) of a vehicle. Design choices in packaging and styling are closely linked to consumer preferences, particularly those that influence consumers' decisions about the objective qualities of a product (i.e., perceptual attributes). The ability to include perceptual attributes into a design optimization study is a valuable extension of the more traditional engineering approach that looks at only functional attributes. Previous work has studied the quantification of perceived environmental friendliness (PEF) in vehicle silhouette design. In this paper, empirically validated PEF silhouette attributes are included as constraints in a vehicle optimization model that maximizes fuel economy. Results indicate that there is a tradeoff between PEF preferences and the attainable fuel economy for a given vehicle, where increasing vehicle length leads to increasing PEF and decreasing fuel economy. [DOI: 10.1115/1.4006146]

1 Introduction

Engineering optimization models typically focus on functional or "objective" design attributes. In addition to these objective attributes, humans (designers or users) make decisions based on subjective attributes (i.e., attributes that each individual evaluates based on her opinion). Of specific interest are perception-based or perceptual attributes, which we define as design properties that can influence people's judgments about objective qualities of a product [1]. Inclusion of perceptual attributes is desirable, but their quantification is difficult and requires methods from the behavioral sciences. Omitting perceptual attributes can lead to designs that align with the engineering or management goals but do not appeal to users. Designers and users can perceive products differently [2]. Consumers often use subjective reasoning to make decisions about products they purchase. While they may start the decision process using objective attributes (e.g., "I need a fuel efficient car that gets at least 25 mpg"), when presented with many similar alternatives, consumers may use subjective attributes to narrow down a choice set (e.g., "I want to drive a car that looks 'green' so that when people see me driving by, they will know that I care about the planet") [3–5]. This situation poses a challenge to designers and engineers, who may focus on different attributes when making design decisions than what customers may focus on when making purchasing decisions. With design having a major influence on sales, designing cars that meet customers' design preferences is important [6].

The need to expand optimization modeling to include engineering, economic, and marketing decisions has been well established, and successful methods for addressing such integration have been developed, particularly in the automotive vehicle field [7–9]. The introduction of powertrain configurations that are different from those dependent solely on internal combustion engines have brought increased design freedom, not just in the powertrain itself, but also in spaces within a vehicle that were previously constrained by the powertrain technology. For example, while the conceptual "skateboard" design is still far from reality [10], designs with in-hub electric motors are within production reality and have few of the classical space arrangement (packaging) restrictions of today's designs.

In automotive design, designers (the "stylists" in automotive body design jargon) create the initial exterior style of the vehicle largely based on perceptual, subjective attributes, and engineers inform them of the constraints in creating the shape for the components largely based on functional, objective, attributes [11]. The resulting product may differ significantly from what each group initially preferred. From an engineering design perspective, this exchange can be improved if we can quantify styles in ways that are explicit and can produce repeatable results. Efforts to include consumer preference and other subjective attributes in optimization models have been previously expended [7,12,13]. The opportunity to include "green" styling criteria in optimization models is presented here based on a previous study that examined the quantification of perceived environmental friendliness (PEF) of vehicle design silhouettes [1]. The PEF measurement serves as a guide to help designers, such as automakers, in the decision-making process and provides them a starting point in the analysis.

Design of a fuel efficient vehicle is a multidisciplinary problem [14–17]. Several researchers have developed models that combine engineering, marketing, and policy models to describe the impact of multiple stakeholder decisions on the design of a fuel efficient vehicle [15,18–21]. Georgiopoulos showed how engineering functionality can be linked with the firm's decision-making processes

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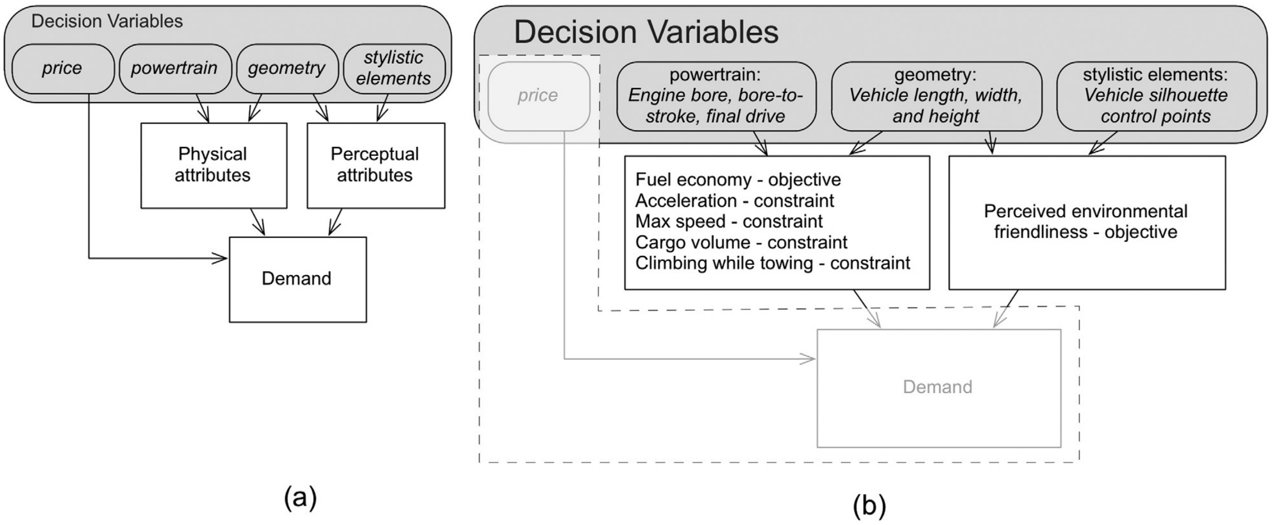

Fig. 1 (*a*) Flow diagram showing the role of perceptual attributes on product demand and (*b*) flow diagram showing the scope of the this article

under government regulations [18]. Frischknecht [21] expanded the models developed earlier by Michalek [20] and Georgiopoulos [18], and developed an integrated vehicle design optimization framework that allows for tradeoffs as perceived by designers, producers, and consumers [21]. A modified version of this market systems framework is used in the optimization studies presented here with the new inclusion of the PEF attributes.

The remainder of this paper is divided as follows: Sec. 2 provides background on the market systems framework used in the study; Sec. 3 discusses modifications made to the framework for the purposes of the current study; Secs. 4 and 5 discuss the optimization studies that were run and their results; and Secs. 6 and 7 provide a discussion and conclusions.

2 Background on the Market Systems Framework

The market systems framework consists of quantitative models that support the decision making process of a firm. In this study, models for product design and sustainability in the form of fuel economy are considered in the analysis. Engineering design is described using a vector of performance criteria described as $\mathbf{z} = \mathbf{f}(\mathbf{x})$, where $\mathbf{x}$ are product design variables. Product design variables are measurable quantities that are under the designer's control [22]. The design variables used in this study are related to engine performance and vehicle geometry, both of which affect fuel economy. The model uses a total of seven design variables which will be discussed later. It is assumed that the engineering models of vehicle performance are sufficient for describing the relationship between product design decisions and product attributes. Product attributes are features that a customer considers in purchasing decisions [9]. The model is based on five-passenger midsize crossover vehicles and the main product attributes examined include: fuel economy, acceleration, maximum climbing grade while towing, top speed, crashworthiness, and cargo capacity. Product attributes $\boldsymbol{\alpha}$ are modeled as functions of product design variables $\mathbf{x}$. There were seven design variables considered in this model: Engine bore x_{EB}; final drive x_{FD}; engine bore to stroke ratio x_{EBS}; vehicle length x_{L103}; width x_{W105}; height x_{H101}; and wheelbase x_{L101}.

The article focuses on fuel economy and packaging using a standard gasoline spark-ignition powertrain. The powertrain model was developed using powertrain specifications and vehicle parameters similar to the 2007 Ford Edge. Two performance tests simulated the US city driving cycle and the US highway driving cycle used by the Environmental Protection Agency (EPA) to calculate combined fuel economy. A simulated acceleration test was used to compute the vehicle's top speed and the time required to accelerate from 0 to 60 mph. Another simulation was run to calculate the maximum grade possible at 65 mph while towing at full capacity.

Packaging is the part of the design process that considers how people, cargo, and vehicle components will fit into a vehicle structure. In the model, packaging was based on simple assumptions about vehicle geometry, which includes engine length and cargo volume index behind the second row seating, among others. Mass properties of the vehicle were considered, including vehicle curb weight and gross vehicle weight rating that were estimated using regressions based on 2005 light duty trucks from Ward's Automotive Yearbook [23].

3 Model Developments

This section discusses changes made to the market systems framework to accommodate perceived environmental friendliness (PEF) as a perceptual attribute. Figure 1(*a*) shows a diagram that specifies the decision variables of the firm, namely price, powertrain specifications, geometry, and styling. Powertrain and geometry variables directly impact functional product attributes (i.e., fuel economy, acceleration, size), and geometry and styling directly impact perceptual attributes (i.e., visual preference, PEF in this study). The model developments focus on the impact of including perceptual attributes on the design of a fuel efficient vehicle when profit is not an objective, Fig. 1(*b*). The premise for this formulation is to understand the impact of styling criteria for PEF on "actual" environmental friendliness defined as fuel economy. Future research can examine the role of PEF on profit, but a more complete demand model needs to be developed for such a study.

The formal representation of this model is shown in Eq. (1). The objective is to maximize fuel economy (FE) with respect to design variables $\mathbf{x}$ (the seven previously mentioned) and for given values of parameters $\mathbf{p}$, subject to engineering constraints and those imposed by PEF. We later explore the tradeoff between fuel economy and PEF directly by treating them both as objectives.

$$\begin{aligned} &\max_{\mathbf{x}} \; FE(\mathbf{X};\mathbf{p}) \\ &\text{subject to:} \quad \textit{engineering constraints} \\ &\qquad\qquad\qquad \textit{PEF constraints} \end{aligned} \tag{1}$$

3.1 Geometry Considerations. Figure 2 shows the Society of Automotive Engineers (SAE) J1100 [24] dimensions applied to

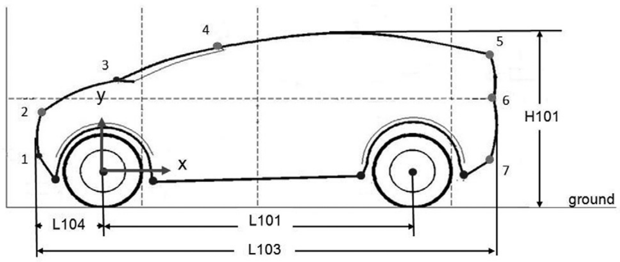

Fig. 2 SAE dimensions used to describe the silhouette geometry

a vehicle silhouette. Dimensions used in the model are $L101$, the length of the wheelbase; $L103$, the overall length of the vehicle; $L104$, the distance from the center of the front wheel to the bumper (i.e., the front overhang); and $H101$, the overall vehicle height. The track width $W101$ and body width $W105$ are included in the vehicle performance model but are not part of the PEF model because the PEF model is based on the two-dimensional silhouettes.

The dimensions $H101$ and $L103$ provide the geometric basis for studying the influence of PEF on the design of a fuel efficient vehicle. These dimensions, used directly in the market systems framework, were converted into functions of the silhouette control points Eqs. (2) and (3). It was observed that using the x coordinates of points 1 and 6 provides the best estimate for the overall vehicle length as shown in Eq. (2). Equation (3) is used to compute the overall height which requires the identification of the highest point P_{top}. A constant $C = 1.21$ is included in both equations. This represents a conversion factor to convert dimensions of silhouettes to units of millimeters and to ensure they are scaled to fit within the acceptable range defined by upper and lower bounds in the market systems framework for midsize crossover vehicles.

$$L103 = \|x_{P6} - x_{P1}\| \times C \tag{2}$$

$$H101 = \left(y_{P_{\text{top}}} - \text{ground}\right) \times C \tag{3}$$

Identification of point P_{top} is done easily for designs already generated, but identifying P_{top} is difficult when the highest point is unknown prior to optimization. The highest point of the vehicle may vary as new designs are generated. There are three variations that have been observed: When point 4 is higher than point 5, when point 5 is higher than point 4, and when a point between them (a midpoint not labeled) is the highest. This last variation in shown in Fig. 2. An engineering constraint requires a minimum vehicle height that allows a driver or passenger to sit comfortably. Since P_4 is located in the region just above the driver seat, we set $P_{\text{top}} = P_4$ to ensure that the seating height criterion is met (see Sec. 4.1).

Equation (4) therefore will be used in the model rather than Eq. (3).

$$H101 = (y_{P_4} - \text{ground}) \times C \tag{4}$$

The cargo volume calculation for the original model assumes a square back end of the vehicle. Cargo volume behind the second row is calculated for a wagon-style vehicle making allowances for the wheel wells, headliners, and other wall thickness. The cargo volume calculation for the revised model is updated to take into account the control point $P5$, which affects the curvature of the back end of the vehicle. This is done by partitioning the cargo volume into three sections: (1) the load floor to a height of $P6x$ treated as an extruded rectangle; (2) the height of $P6x$ to the height of $P5x$ treated as an extruded trapezoid; and (3) the height of $P5x$ to the height of $P4x$ treated as an extruded triangle (see Fig. 3). The estimated volume of the wheelhouse, headliner, and other interior trim is removed from the cargo volume calculation.

Two additional changes are made to the vehicle geometry in the revised model compared to the original model. First, the wheelbase $L101$ is given the value 3010 mm and treated as a parameter rather than a design variable. Second, the front overhang parameter $L104$ is changed from a value of 940 to 645 mm. Both changes are made to accommodate the geometry of the vehicle silhouettes used to develop the PEF model, which had a fixed wheelbase and a shorter front overhang compared to the original model (Fig. 2).

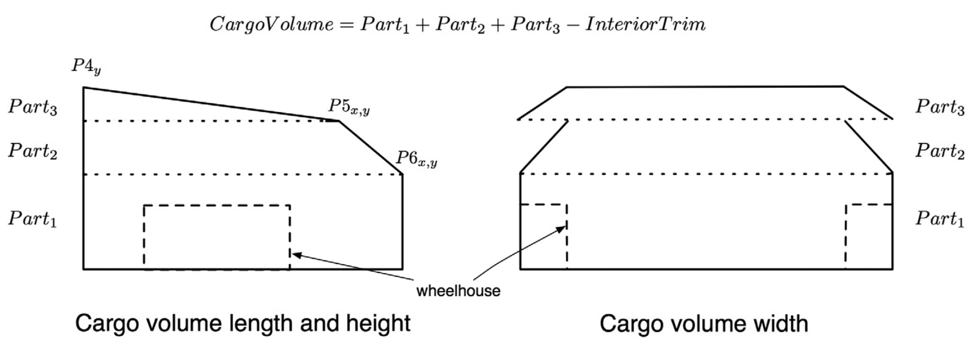

Fig. 3 Stylized vehicle sketch showing the relationship between the cargo volume calculation and the geometry control points included in the PEF calculation

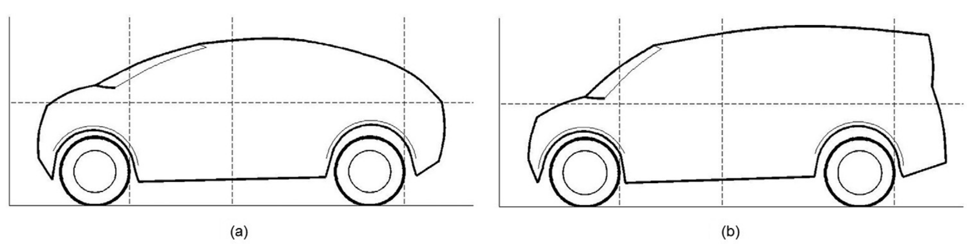

Fig. 4 Silhouettes used in the study [1] with (*a*) *PEF* = 5.12 and (*b*) *PEF* = 2.60, the highest and lowest mean PEF ratings, respectively

Table 1 Demographic information of the 195 respondents

Gender			Age Groups			
F	M	N/A	18–30	31–50	51–70	>70
50%	49%	1%	32%	32%	29%	7%

3.2 PEF Model. The model for PEF was determined from a previous study [1] that involved 195 participants (98 females, 96 males, with one who did not identify gender) ranging in age from 18 to older than 70 years; approximately 20% were from a university setting (e.g. students, professors, postdocs, etc.) and 80% were from a nonuniversity setting with over 60 different job titles. Care was taken to recruit a diverse group of participants based on age, gender, occupation, and geographic locations. Table 1 summarizes the demographic information.

A set of 17 vehicle silhouettes were used in the study, where 16 of them were created according to an experimental design and one was a "plant" (the Toyota Prius). Each silhouette was shown one at a time and participants were asked to answer a variety of questions about them (see [1] for complete details about the study). One of the key questions asked was: "*Based on the visual content, please rate how well this vehicle conveys environmental friendliness.*" Participants were allowed to rate the image on a scale of 1–7 where 1 = Does not convey environmental friendliness to 7 = Definitely conveys environmental friendliness.

Mean ratings were computed for each vehicle and analysis of variance (ANOVA) was used to identify the most significant control points (see control points in Fig. 2) that influenced the ratings. The computed means and values for the control points (see Table 2) were used in a regression analysis represented by Eq. (5):

$$PEF = \beta_0 + \sum_{i=2}^{7} \left(\beta_{ix} P_{ix} + \beta_{iy} P_{iy}\right) \tag{5}$$

where $i = 2, 4, 5, 6, 7$ correspond to the control points and β_0 is the intercept. The x and y coordinates of points 2, 4, 5, 6, and 7 were the most significant.

The regression was run using the most significant control points of a select set of 16 vehicle silhouettes as independent variables and the mean ratings as dependent variables as shown in Table 2. The control points and their coefficients are listed in Table 3. This model has an $R^2 = 0.85$ correlation with actual ratings from the consumer studies. Equation (5) is used to calculate the PEF attribute in the optimization studies.

3.3 Fuel Economy Model. Fuel economy depends on several factors including vehicle mass, power train specification, vehicle frontal area, and drag coefficient. Corporate average fuel economy (CAFE) is a US government standard applied to a firm's US sales of passenger cars and light trucks. The standard is based on the sales-weighted average fuel economy of an automaker's sales in any given model year [25,26]. Standard driving cycles are specified to measure a vehicle's fuel economy for the purposes of the CAFE standard. A simulation for calculating fuel economy was created by [21] using the powertrain simulation package *AVL Cruise* [27] and the two driving cycles specified by CAFE prior to 2008. These tests include the US city driving cycle and the US highway driving cycle. The two measures are used to compute combined fuel economy of a vehicle based on pre-2008 EPA window sticker reporting methods which give a weight of 55% to city driving and 45% to highway driving, Eq. (6):

$$FE = \frac{1}{\dfrac{0.55}{0.9 MPGCycUSCity} + \dfrac{0.45}{0.78 MPGCycUSHwy}} \tag{6}$$

where *MPGCycUSCity* and *MPGCycUSHwy* are, respectively, the test cycle city and highway fuel economies

Polynomial surrogate models built from the *AVL Cruise* simulation data are used in this article for calculating *MPGCycUSCity* and *MPGCycUSHwy*. The specific vehicle characteristics that influenced these models include: Engine bore, engine bore to stroke ratio, final drive, $H101$, $L101$, $L103$, $W105$, and coefficient of drag C_D. Six of these characteristics are design variables used in the model. $L101$ is set as a parameter as explained in Sec. 3.1 ($L101 = 3010$ mm), and the drag coefficient is set as a parameter ($C_D = 0.37$). The drag coefficient is a nondimensional number that

Table 2 Table of means and significant control points used in regression analysis (organized in the order of increasing PEF). Figure 4 shows an image of the highest and lowest PEF vehicles (i.e., vehicle 14 and vehicle 7, respectively).

Actual mean rating	$P2x$	$P2y$	$P4x$	$P4y$	$P5x$	$P5y$	$P6x$	$P6y$	$P7x$	$P7y$	Predicted mean rating	Vehicle No.
2.60	−1.4	1.6	2	3.7	10.0	4.0	10.1	2.5	10.5	0.3	2.68	7
2.82	−1.6	1.9	2	3.7	10.0	3.2	10.5	2.5	10.0	0.4	3.02	5
2.98	−1.6	1.9	2	3.7	10.0	3.2	10.5	2.0	10.5	0.3	2.96	6
3.20	−1.4	1.9	2	3.4	8.5	4.0	10.1	2.0	10.5	0.4	3.42	3
3.32	−1.4	1.6	2	3.7	10.0	4.0	10.5	2.0	10.0	0.4	3.06	8
3.35	−1.6	1.9	3	3.4	10.0	4.0	10.1	2.5	10.5	0.3	3.09	12
3.40	−1.6	1.9	3	3.4	10.0	4.0	10.5	2.0	10.0	0.4	3.48	11
3.53	−1.4	1.9	2	3.4	8.5	4.0	10.5	2.5	10.0	0.3	3.50	4
3.85	−1.6	1.6	3	3.7	8.5	4.0	10.5	2.5	10.0	0.3	4.06	15
3.94	−1.4	1.9	3	3.7	8.5	3.2	10.5	2.5	10.5	0.4	4.29	13
3.99	−1.6	1.6	2	3.4	8.5	3.2	10.1	2.0	10.0	0.3	4.34	1
4.02	−1.6	1.6	3	3.7	8.5	4.0	10.1	2.0	10.5	0.4	3.98	16
4.08	−1.4	1.6	3	3.4	10.0	3.2	10.5	2.0	10.5	0.3	4.29	9
4.37	−1.4	1.6	3	3.4	10.0	3.2	10.1	2.5	10.0	0.4	4.34	10
4.56	−1.6	1.6	2	3.4	8.5	3.2	10.5	2.5	10.5	0.4	4.04	2
5.12	−1.4	1.9	3	3.7	8.5	3.2	10.1	2.0	10.0	0.3	4.59	14

Table 3 List of β values for PEF model

Control point		$P2x$	$P2y$	$P4x$	$P4y$	$P5x$	$P5y$	$P6x$	$P6y$	$P7x$	$P7y$
Coefficient	β_0	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}
Value	18.5	0.743	−1.02	0.641	−0.767	−0.441	−0.719	0.0657	−0.277	−0.415	0.144

is a complex function of detailed vehicle geometry. The drag force on the vehicle is proportional to the product of the drag coefficient C_D and the vehicle frontal area ($W105 \times H101$). The drag coefficient used in all studies ($C_D = 0.37$) is a reasonable value for a midsize crossover vehicle.

4 Optimization Study

Three optimization formulations are examined. The first two are single-objective optimization formulations that maximize fuel economy without PEF constraints. The first presents the results using the original fuel economy model developed in [21]. The second examines the performance of a revised fuel economy model modified to replace $L103$ and $H101$ with Eqs. (2) and (4), respectively, and is used as a basis for comparison of subsequent optimization studies. The third formulation is a bi-objective optimization problem where we use the upper bound (or ϵ) constraint method to identify Pareto solutions. The results show a tradeoff that exists between the two objectives of interest: fuel economy and PEF. The Pareto set is generated using PEF as a constraint and conducting a parametric study on the bound on PEF, which will have to be active if a tradeoff between fuel economy and PEF exists [22,28].

Section 4.1 reports the results for the first two formulations; Sec. 4.2 reports the results for the third formulation. Section 4.3 reports the results for the Pareto study.

4.1 Maximizing Fuel Economy. The first formulation uses the model as described in Sec. 3, and the second uses a modified version of this model which replaces $L103$ and $H101$ with Eqs. (2) and (4), respectively. The objective is to maximize fuel economy with respect to design variables **x** and parameters **p,** subject to engineering constraints [Eq. (7)].

$$\begin{aligned} &\max_{\mathbf{x}} \ FE(\mathbf{x};\mathbf{p}) \\ &\text{subject to}: \ \textit{engineering constraints} \end{aligned} \tag{7}$$

The design variables of interest from the original model are engine bore x_{EB}; final drive x_{FD}; engine bore to stroke ratio x_{EBS}; vehicle length x_{L103}; width x_{W105}; height x_{H101}; and wheelbase x_{L101}. These dimensions serve as inputs to a number of other design criteria including cargo volume, top speed, and vehicle mass, which in turn impact safety criteria and vehicle center of gravity. Therefore, changes in these variables will impact not only fuel economy but other vehicle attributes as well. Recall that, in the modified model, x_{L103} and x_{H101} are defined as functions of control points $P6x$ and $P4y$, respectively, see Eqs. (2) and (4). This allows the computed positions of the control points to dictate the values for $H101$ and $L103$, thus capturing the influence of PEF in the model. The value for the wheel base p_{L101} is included as a parameter in the model as is the drag coefficient p_{CD}.

The remaining x and y coordinates of the silhouette control points influence the PEF function. These values are also included as variables. Table 4 shows the complete set of variables considered and their lower and upper bounds.

Equations (8)–(23) list the constraints in the original fuel economy maximization model. They represent performance criteria and other vehicle characteristics that are typical for a crossover vehicle. Specifically, the constraints consider: Safety, Eqs. (8)–(10); performance, Eqs. (11)–(14); geometry, Eqs. (16)–(21); and cargo volume, Eqs. (22) and (23). Other constraints in the original model were relaxed to allow for a greater degree of design freedom.

$$g_1: \ \textit{Rollover} - 0.21 \leq 0 \tag{8}$$

$$g_2: \ \textit{MinCrushSpace} - \textit{CrushSpace} \leq 0 \tag{9}$$

$$g_3: \ \textit{AccelTestFront} - 9.81 \ * \textit{MaxAccelTestFront} \leq 0 \tag{10}$$

Table 4 List of design variables and their bounds

Variable	Description	Lower bound	Upper bound
x_{EB}	Engine bore	86	100
x_{FD}	Final drive	1.1	4.0
x_{W105}	Vehicle body width	1600	2000
x_{EBS}	Engine bore stroke ratio	0.95	1.18
x_{P2x}	x coordinate of point 2	−1.6	−1.4
x_{P2y}	y coordinate of point 2	1.6	1.9
x_{P4x}	x coordinate of point 4	2.0	3.0
x_{P4y}	y coordinate of point 4	3.0	4.1
x_{P5x}	x coordinate of point 5	8.5	10.0
x_{P5y}	y coordinate of point 5	3.2	4.0
x_{P6x}	x coordinate of point 6	10.0	10.5
x_{P6y}	y coordinate of point 6	2.0	2.5
x_{P7x}	x coordinate of point 7	10.1	10.5
x_{P7y}	y coordinate of point 7	0.3	0.4

$$g_4: \ 5\% - \textit{Grad65Tow} \leq 0 \tag{11}$$

$$g_5: \ \textit{MinCargoMass} - \textit{VehCargoFullMass} \leq 0 \tag{12}$$

$$g_6: \ \textit{Acc3050Tow} - \textit{Max30to50} \leq 0 \tag{13}$$

$$g_7: \ \textit{MinTopSpeed} - \textit{MaxTopSpeed} \leq 0 \tag{14}$$

$$g_8: \ 13^o - A107 \leq 0 \tag{15}$$

$$g_9: \ 12^o - A147 \leq 0 \tag{16}$$

$$g_{10}: \ 50\% - 100\left(1 - CG_{\mathrm{long}} - L104/L101\right) \leq 0 \tag{17}$$

$$\begin{aligned} g_{11}: \ &(2\textit{TireFlop} + 2\textit{MidRailWidth} + \textit{EngLength} + 50.8) \\ &- (W105 - 254) \leq 0 \end{aligned} \tag{18}$$

$$g_{12}: \ L101 + L104 - L103 \leq 0 \tag{19}$$

$$g_{13}: \ \textit{MinSitHeight} - H101 \leq 0 \tag{20}$$

$$g_{14}: \ (\textit{TireDynRollRad} + 10 * 25.4) - L104 \leq 0 \tag{21}$$

$$g_{15}: \ 29 \text{ ft}^3 - CVI \leq 0 \tag{22}$$

$$g_{16}: CVI - 60 \text{ ft}^3 \leq 0 \tag{23}$$

A constraint was added to the revised model to ensure that x_{P4y} remains the highest point on the vehicle given that we associate x_{P4y} directly with $H101$, Eq. (24):

$$g_{17}: \ x_{Py} - x_{p4y} \leq 0 \tag{24}$$

The results of optimization are shown in Table 5. The first column labeled as "MPG only original" contains the results using the original model. Table 5 reveals that the combined fuel economy is 23.1 mpg with the city and highway fuel economy being 21.6 and 25.1 mpg, respectively. Here, and subsequently, the city and highway fuel economies reported have already been adjusted by the 0.9 and 0.78 correction factors, respectively, from Eq. (6). The geometry variable values are overall vehicle length $L103 = 4712$ mm, vehicle width $W105 = 1887$ mm, and overall height $H101 = 1704$ mm.

Performance attributes are time to accelerate from rest to 60 mph of 10.0 s, maximum speed of 127 mph, tow grade of 5 deg, and a minimum cargo volume of 29 ft^3.

There were six active constraints. Note that a constraint is active when its removal from the optimization affects the value of the optimum [22]. The active constraints are max gradeability, which estimates the percent grade achievable at 65 mph while towing a trailer [Eq. (11)], minimum cargo volume [Eq. (22)], maximum rollover score [Eq. (8)], minimum seating height [Eq. (20)], the lower bound on the engine bore, and the upper bound on the bore to stroke ratio.

The results of the revised model are listed in the second column under the heading "MPG only revised." The combined fuel

Table 5 Optimization study results. The arrows indicate the direction of variable values under max PEF conditions.

Description	Variables	Units	Study 1 MPG only original	Study 2 MPG only revised	Study 3a MPG with 4.0-PEF	Study 3b MPG with 4.3-PEF
Objective	Combined FE	mpg	23.1	23.6	23.3	22.5
	MPG city	mpg	21.6	22.1	21.9	21.2
	MPG hwy	mpg	25.1	25.7	25.4	24.3
Design variables	L103	mm	4712	4420	4571	4571
	W105	mm	1887	1881	1886	1998
	H101	mm	1704	1704	1704	1704
	Eng bore	mm	86	86	86	86
	Eng bore stroke	–	1.18	1.18	1.18	1.15
	Final drive	–	3.57	3.59	3.65	3.70
	$P2x(\uparrow)$	–	–		−1.40	−1.40
	$P2y(\downarrow)$	–	–		1.60	1.60
	$P4x(\uparrow)$	–	–		3.00	3.00
	$P4y(\downarrow)$	–	–	3.92	3.92	3.92
	$P5x(\downarrow)$	–	–	10.0	10.0	8.50
	$P5y(\downarrow)$	–	–	3.92	3.30	3.59
	$P6x(\uparrow)$	–	–	10.1	10.5	10.5
	$P6y(\downarrow)$	–	–	2.45	2.00	2.50
	$P7x(\downarrow)$	–	–		10.1	10.1
	$P7y(\uparrow)$	–	–		0.40	0.40
Performance measures	Accel: from 0–60 mph	sec	10.0	9.7	9.9	9.8
	Max Speed	mpg	127	129	128	125
	Tow grade	degrees	5	5	5	5
	CVI	ft^3	29	29	29	29
Parameters	$L101$	mm	2754[a]	3010	3010	3010

[a]$L101$ was treated as a design variable in study 1.

economy is 23.6 mpg with the city and highway fuel economy being 22.1 and 25.7 mpg, respectively. Compared to the original model, the revised model achieves better fuel economy. This is due to a shorter front overhang $L104$, which leads to a smaller, i.e., lighter, vehicle. The vehicle length and track width $L103 = 4429$ mm and $W105 = 1882$ mm are both shorter. The value of the overall height remains the same. The active constraints and variable bounds are identical to the original model with the addition of an active roof height constraint [Eq. (24)] and $P5x$ and $P6y$ at their upper bounds. Since the PEF constraint was not used in study 2, only five values of the control points are shown since they are related directly to $H101$, $L103$, and cargo volume. The other five control points are not shown because their values do not influence the fuel economy model.

These results provide a baseline for how the fuel economy model performs under the conditions presented. We now examine how the design changes with the inclusion of PEF as a constraint.

4.2 Maximizing Fuel Economy With a PEF Constraint. The objective is to maximize fuel economy with respect to design variables **x** and parameters **p,** subject to engineering constraints and a PEF constraint based on Eq. (5). The inclusion of a PEF constraint represents the inclusion of the visual requirements necessary to capture the green styling cues of interest to the customer. The intent is to consider objective and subjective attributes concurrently in the optimization study.

Interestingly, there are no feasible solutions to the vehicle design problem using the original bounds for the control points as reported in an earlier study [1] and shown in Table 4. This is because some of the engineering constraints that are functions of $H101$ are violated. Recall that $H101 = f(P4y)$. Therefore, the original bounds on $P4y$ were relaxed to $3.2 \le P4y \le 4.1$ and the lower bound on $P6x$ was relaxed to 10. The original bounds for $P4y$ were $3.4 \le P4y \le 3.7$ and the original lower bound on $P6x$ was 10.1.

The highest attainable value from the PEF model [Eq. (5)] is 4.74. This value is obtained by setting all the control points to their upper or lower bounds for variables that had positive or negative coefficients, respectively. Therefore, the PEF bound constraint is set to be at a value lower than that to ensure feasibility; specifically, the PEF bound is set as $PEFMin = 4.0$:

$$g_{18} : PEF\min - \sum_{i=2}^{7} \beta_{ix} P_{ix} + \beta_{iy} P_{iy} \le 0 \tag{25}$$

where $i \neq 3$.

The results from the revised fuel economy model with a constraint on PEF with two different lower bounds 4.0 and 4.315 are presented in Table 5. Upon inspection of Table 5, it can be seen that there is some change in the fuel economy with the inclusion of the PEF constraint as defined in Eq. (25). This is primarily due to an increase in vehicle length from $L103 = 4420$ to $L103 = 4571$, which increases vehicle mass. The same constraints and variable bounds are active as for the second formulation. Additionally, several silhouette control points hit their upper ($P2x$, $P4x$, $P5x$, $P7y$) or lower ($P2y$, $P6y$, $P7x$) bounds.

The model was rerun with a larger PEF bound: $4.315 - PEF \le 0$. This value represents the maximum feasible PEF value. The results are listed in the column labeled "MPG with 4.3-PEF" and it can be seen that as PEF increased, the fuel economy decreased. This is primarily caused by vehicle width increasing from $W105 = 1886$ mm to $W105 = 1998$ mm. Increased vehicle width increases vehicle mass and drag. The overall length is already close to the upper bound for $P6x$ when $PEFMin = 4.0$, so the width dimension is the means to satisfy the cargo volume constraint when $P5x$ decreases in order to improve PEF. The wider vehicle means the rollover constraint is no longer active. Also, the larger vehicle size requires a larger engine to meet the performance requirements, so the upper bound on the engine bore to stroke ratio is no longer active. Engine bore, $P2y$, $P5x$, and $P7x$ are all at their lower bounds, and $P2x$, $P4x$, $P6x$, $P6y$, and $P7y$ are all at their upper bounds.

Note the arrows located next to the control points $P4y$ and $P6x$ in Fig. 5. The darker shaded arrow indicates the direction the value of the control point should take in order to maximize PEF; the lighter shaded arrow indicates the value $P6x$ should take to maximize fuel economy. This is in accordance to the signs of the coefficients in Table 3.

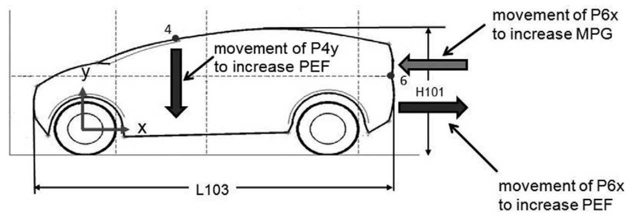

Fig. 5 Pictorial representation of tradeoffs between PEF and MPG through *P6x* and *P4y*. Refer to Fig. 7 for examples.

It seems counterintuitive that a higher PEF vehicle would get longer when we expect a smaller car to be greener. One of the conclusions from the earlier study [1] was that vehicles that had more curved lines were perceived as more environmentally friendly than those with abrupt changes. An increase in $P6x$ would cause the segment between point 5 and point 6 to stretch and produce more of a smooth curve. Similarly, the position of $P5$ affects the rear curvature of the vehicle. Vehicle shapes that have lower $P6x$ and larger $P5x$ and $P5y$ values tend to make the segment from point 4 to 6 get boxy. In the study presented in [1], there were only two possible values for $P6x$: 10.1 or 10.5. Most vehicles with best PEF (i.e., mean ratings ≥ 4) had $P6x$ values of 10.1 and two had $P6x$ values of 10.5 (see [29] and Table 2).

4.3 Parametric Study on PEF: Pareto Points. A parametric study is conducted to examine how changes in the PEF bound parameter value affect the optimum. This is equivalent to examining a range of solutions to the bi-objective optimization of maximizing both fuel economy and PEF. As noted, in a bi-objective problem $\max[f_1, f_2]$, Pareto points can be computed by solving the problem $[\max f_1$, sub. to $f_2 \geq F_2]$ for different values of the parameter F_2.

The minimum PEF bound value is changed from 3.3 to 4.315. Figure 6 shows the results. The points with the PEF bound above 3.4 in Fig. 6 represent Pareto points for the problem max $\{MPG, PEF\}$.

Changes in the PEF constraint do not affect the optimum fuel economy when $PEF_{\min}$ is below 3.4. In this range, several constraints are always active: Minimum tow grade [Eq. (11)], maximum rollover score [Eq. (8)], minimum seating height [Eq. (20)], and minimum cargo volume [Eq. (22)]. The PEF constraint becomes active under two conditions: When the control points hit their bounds and when the optimizer finds a combination of values that produces an exact minimum PEF value. The lower bound on the engine bore variable and the upper bound on the engine bore-to-stroke ratio also remain active.

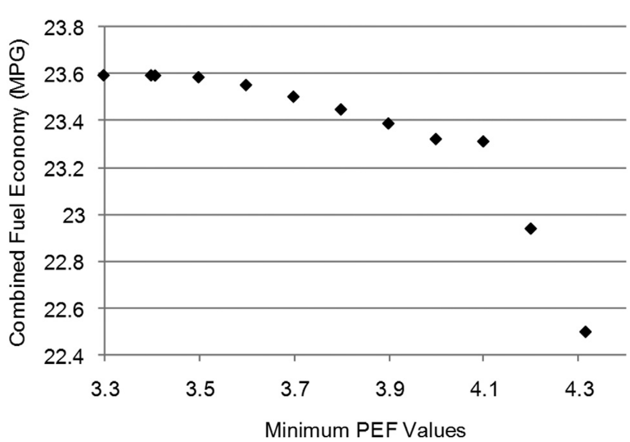

Fig. 6 Results of a parametric study done on the PEF constraint

When $PEF_{\min}$ is varied from 3.41 to 4.315, there is a tradeoff between PEF and fuel economy. As PEF increases, the fuel economy decreases. The main variables influencing this tradeoff are $P6x$, which affects vehicle length and cargo volume, and $P5x$ and $P5y$, which affect cargo volume. In essence, as the length of the vehicle increases and the back of the vehicle becomes more sloped, PEF increases. The overall vehicle dimensions ($L103$ and $W105$) must increase to satisfy the cargo volume constraint, and therefore the fuel economy decreases. An increase in vehicle height would penalize both fuel economy and PEF, so the minimum sitting height constraint remains active in all scenarios.

5 Optimal Silhouettes

We are interested in visually examining the vehicle silhouettes implied by the optimization study. A vehicle silhouette can be generated using 14 x and y coordinate values with a 15th variable that controls the roof curvature. The factor levels used in the survey provide the acceptable bounds for generating new silhouettes. The optimization study provides values within these bounds for generating new silhouettes. The values of the control points in Table 5 are used to generate new designs that consider fuel efficiency. The other five variables are held fixed as parameters. Figure 7(*a*) shows the “MPG with 4.315-PEF” silhouette and Fig. 7(*b*) shows a silhouette using the control points identified in the “MPG with 4.0-PEF” analysis. Figure 7(*c*) shows the silhouette when $PEFMin = 3.41$, which is effectively the MPG only-revised silhouette since it achieves the same fuel economy of 23.6 mpg.

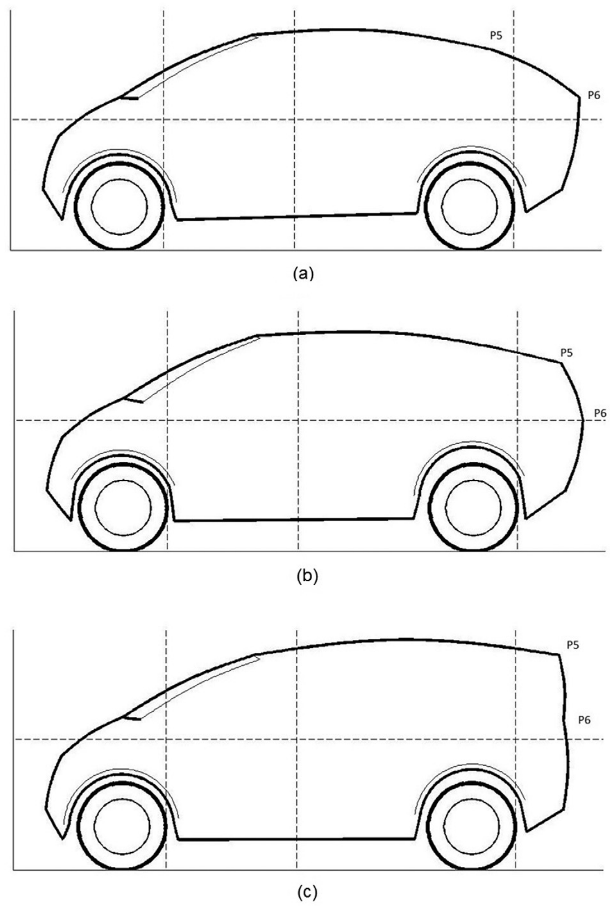

Fig. 7 Silhouettes for vehicles maximizing fuel economy with increasing levels of the PEF constraint: (*a*) *PEF* ≥ 4.315, (*b*) *PEF* ≥ 4.0, and (*c*) *PEF* ≥ 3.41

6 Discussion

The study shows how PEF can be included in an optimization model for designing a fuel efficient vehicle. PEF was included in the model by mapping the control points to geometries considered in the model, namely, the overall height dimension $H101$, the overall length dimension $L103$, and the cargo volume calculation. The revised fuel economy model produced a more fuel efficient vehicle than the original one due to the change in the front overhang parameter $L104$, which was necessary to match the silhouettes. $H101$ had a single optimal value and did not change between models.

The PEF constraint affected the fuel economy depending on its minimum value. A first result showed that increasing PEF caused a decrease in fuel economy. The parametric study showed that when PEF's minimum value was in the range of less than 3.41, it achieved the same fuel economy: 23.6 mpg. The minimum cargo volume constraint was active and dominated the PEF constraint which was inactive or conditionally active. However, when the minimum PEF value was in the range $3.41 \leq PEF \leq 4.315$, there was a tradeoff between PEF and fuel economy. As PEF increases, fuel economy decreases and the vehicle becomes longer and wider. The achievable fuel economy for this model ranged from 22.5 to 23.6 mpg.

The behavior of the functional attribute fuel economy supports the notion that small vehicles are preferred as friendlier for the environment. The combination of functional and perceptual attributes in the optimization model suggests that, given two small vehicles, one that is actually a bit bigger but looks smoother may be perceived as more environmentally friendly.

Improving the PEF score while maintaining the maximum fuel economy would require a reduction in cargo volume. A product development challenge is then to understand how the customer may balance preferences between fuel economy, cargo volume, and PEF.

Optimal silhouette designs were generated based on PEF and fuel economy. The survey results from the earlier cited study [1] provided the acceptable range of values for each of the ten control points that were included in the model here to ensure that PEF optimal designs would be generated (see also Table 2). Two control points, $P4y$ and $P6x$, were linked to $H101$ and $L103$, respectively, and their placement was influenced by engineering criteria for the design of a fuel-efficient vehicle. The control points $P4y$, $P5x$, $P5y$, $P6x$, and $P6y$ were linked to the cargo volume calculation and were influenced by the cargo volume constraint. Differences in these control points constitute the main observable differences between the vehicle silhouettes for differing levels of fuel economy and PEF. Silhouettes that have increased PEF values increase the value of $P6x$ and decrease the values of $P5x$ and $P5y$ to ensure the vehicle has a curved look. The increase in $P6x$ increases the vehicle length, and the decreases in $P5x$ and $P5y$ increase the vehicle width, which in turn reduces fuel economy.

7 Conclusions

The work presented here demonstrated how customer perceptual attributes can be included in an optimization study. We specifically showed how a perceptual attribute like PEF influences vehicle optimal design and that a tradeoff exists between PEF and fuel efficiency. This ability to study the influence of desirable green styling criteria in an optimization model is an important extension to purely engineering design studies.

The study showed that a crossover vehicle that takes a more streamlined shape (i.e., has a shorter vertical dimension and longer horizontal dimension) is perceived as more environmentally friendly, based on a previous study [1]. There were seven design variables used in the optimization model: Engine bore x_{EB}; final drive x_{FD}; engine bore to stroke ratio x_{EBS}; vehicle length x_{L103}; width x_{W105}; height x_{H101}; and wheelbase x_{L101}. Of the variables listed, the wheelbase was held constant, and the remaining six were determined by the optimization algorithm. Satisfaction of the PEF objective required adjustment to $P5$ and $P6$, thus achieving a more streamlined appearance. The movement of $P5$ and $P6$ caused the width of the vehicle to increase so that the cargo volume constraint would be satisfied. Increasing both width and length increases the vehicle mass which in turn decreases the fuel efficiency.

Design results were based on a model with a number of assumptions, and so a number of limitations must be noted. The data to support the PEF model was aggregated across individuals. Future studies could develop PEF models that reflect heterogeneity in the sample population, perhaps using a utility function [30]. We presented our approach as an initial offering that can be improved in future work. For example, we recognize that when we aggregate data across individuals and then use it in a decision-making context we are making one of two assumptions. Either we assume that the population has the same preferences up to an unobserved stochastic component (from an economist's perspective) or up to an individual idiosyncratic component (from a psychologist's perspective), or we assume that the arithmetic mean is the appropriate way to aggregate a population's preferences for use in decision making. If the first assumption holds then the PEF model does provide a consistent ordering of a set of alternatives according to the PEF construct. However, given taste heterogeneity, the second assumption opens up the model for critique based on Arrow's Impossibility Theorem [31] unless we are claiming a cardinal utility measure rather than the traditional ordinal utility measure. Yet, our paper is not focused on a heterogeneous description of the population or a measurement of consumer welfare. Rather, we operationalize the PEF construct for use by a single decision maker.

Another limitation is that actual silhouettes may not fully conform to the assumptions made in the model. The vehicle proportions between the front, mid, and rear overhangs shown in the generated silhouette are not analogous to those exhibited in existing internal combustion engine vehicles. The positioning of key features on the vehicle such as the cowl point, the front overhang, and the windshield are not in compliance with typical manufacturing standards. The shapes created would be more suitable for "futuristic" vehicle designs, such as the "skateboard" technology based on hydrogen fuel cells where the powertrain no longer limits the shape of a vehicle (see [10,32] for examples of images).

The market systems framework studies how designs can affect the profit of a firm. It is therefore plausible that the optimization results achieved here would change once profit is taken into consideration. Future studies should examine the impact of PEF on the profitability of the firm. One way to examine this is by correlating the performance of fuel efficient-PEF designs with the performance desired by consumers as shown in revealed preference data. Based on the work done by [21] and [33], we conjecture that the designs generated in this study may negatively impact the profit of the firm due to some performance inadequacies. The work reported by Ewing and Sarigöllü [33] demonstrated that consumers were not willing to trade-off standard performance criteria like acceleration. The 0–60 mph accelerations listed in Table 5 are below values considered competitive for crossover vehicles where 8 s is typically expected [21].

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